Presented at the 31st Explosives Safety Seminar,
August 2004, San Antonio, Texas

BLUNT TRAUMA FROM BLAST-INDUCED BUILDING DEBRIS

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Protecting building occupants from blast effects is a primary focus of current research. One of the primary injury mechanisms is blunt trauma, as structural and architectural elements of the building as well as building contents are projected by the force of the blast and impact humans inside the building. A series of experiments was performed recently in which instrumented anthropomorphic test devices (ATDs) were placed in cubicles and subjected to impacting debris from windows and wood stud walls to observe their response. Injury levels were estimated using established human injury criteria and scaling techniques, some of which have been validated through years of automotive safety testing.

The tests provided a significant number of data points (21 in all) that allow the quantification of relationships between blunt trauma injury levels and the blast impulse on the building. By testing various configurations of windows, the data supports conclusions regarding the effect of window parameters on injury level, such as annealed vs tempered glass, glass thickness, and size. Additionally, a number of retrofit concepts were tested, including anti-shatter film using both daylight and restrained application, and shielding by computer equipment. One test exposed an ATD to wood stud wall debris.

Taken as a set, these tests provide a coherent and well documented data set with important implications regarding the efficacy and potentially deleterious effects of commonly used retrofit techniques with regard to the blunt trauma levels received by occupants.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2004**	2. REPORT TYPE	3. DATES COVERED **00-00-2004 to 00-00-2004**

4. TITLE AND SUBTITLE **Blunt Trauma From Blast-Induced Building Debris**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Karagozian & Case,2550 N. Hollywood Way, Suite 500,Burbank,CA,91505**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 31st Explosives Safety Seminar, held in San Antonio, Texas, on August 2004. Federal Purpose Rights

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**19**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

INTRODUCTION

Protecting people from blast effects is a primary focus of current research. While direct blast effects can be injurious (e.g., causing ear drum damage or, in the case of more severe pressures, lung damage), the primary injury mechanism for occupants of a building subjected to an external blast is blunt trauma, as structural, mechanical, and architectural elements of the building (along with building contents such as furnishings) are projected by the force of the blast and impact humans inside the building.

To better understand the mechanics of these impacts, and to document the relationship between lethality and key parameters such as mass, velocity, and type of debris, a series of experiments were conducted in which instrumented anthropomorphic test devices (ATDs) were exposed to blast-induced debris. The tests focused primarily on glass debris from windows, and they also focused on blunt trauma to the head.

An earlier paper [1] had presented some interim results from this test series along with tentative conclusions. Since then, additional tests have been conducted and the experimental database expanded significantly. This paper uses this augmented data set to draw broader conclusions and reinforce the earlier ones. Our intent is to utilize the various test results to assess the sensitivity of lethality to key parameters for typical windows.

OVERVIEW OF TEST SERIES

The tests in question were part of the DIVINE BUFFALO series and were performed at Kirtland Air Force Base in New Mexico. In particular, tests 21, 24, and 28–31 involved instrumented ATDs exposed to glazing or other debris propelled by blast effects. A typical test layout is shown in Figure 1, where the individual cubicles (typically four per test) were arrayed at various standoffs from the charge. The primary purpose of the tests was to expose reinforced concrete columns to blast loads; the cubicles were add-on experiments for expediency’s sake.

Each cubicle contained a single anthropomorphic test dummy (ATD) exposed to debris from a window on the front face of the cubicle. Photographs of a typical cubicle exterior and interior are shown in Figure 2. The same charge weight was used in all the tests, such that the only environment variable was the standoff.

In referring to these cubicles, we will use the shorthand “DB XX/Y” where XX is the test number and Y is the cubicle number. For instance, cubicle 3 in DIVINE BUFFALO 28 will be designated DB 28/3.

Not all the cubicles were used for human injury purposes, but all in all, the six tests provided a total of 21 individual injury-related experiments, each with a single instrumented ATD. Due to consistency in the experimental method, the explosive charge used, the type and size of the cubicles, and the measurement techniques, the result is a data set that is uniquely broad and consistent and, therefore, well suited for comparisons and drawing conclusions.

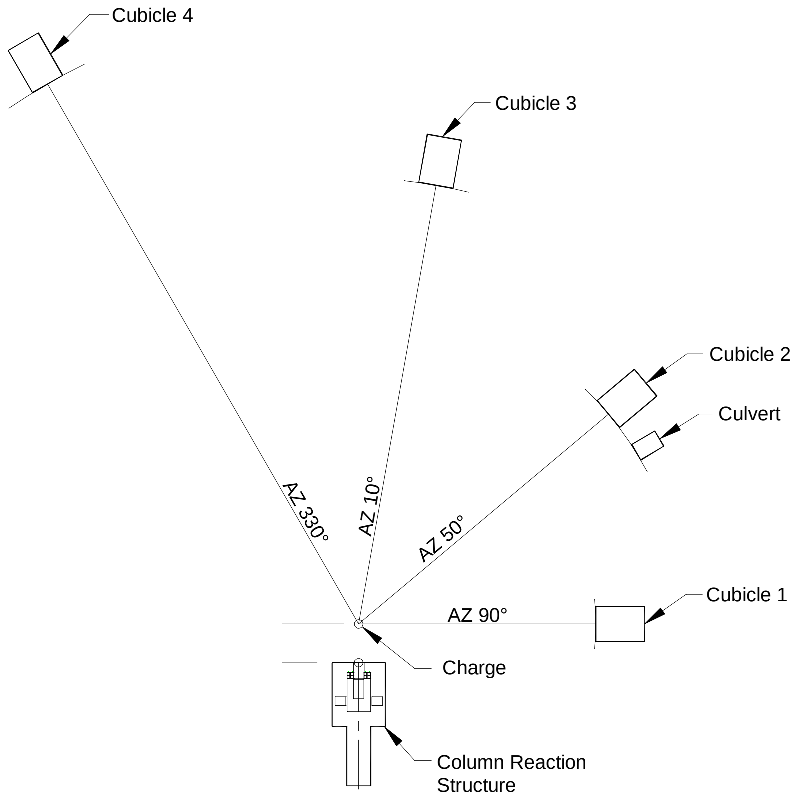


Figure 1. Layout of typical DIVINE BUFFALO test with cubicles.

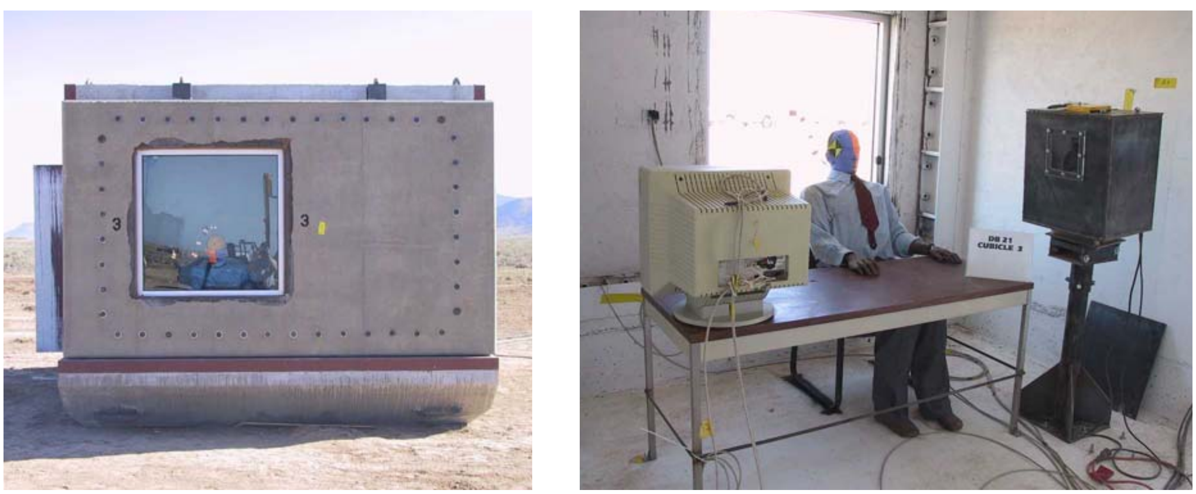


Figure 2. Typical cubicle appearance, exterior and interior.

The ATDs used were Hybrid II models, instrumented with accelerometers in the head to measure motion in all three directions. These acceleration records were used subsequently to estimate the level of injury sustained. The ATDs were positioned in a fashion that might be typical for an office environment: seated, opposite and near the window, and facing away from the window. A table (bolted to the floor) was provided in front of each ATD to limit the total rigid body displacement after impact of the glass.

The primary variation between experiments was the type of glass used for the window. The typical window was 4 ft square (as illustrated in Figure 2), thermally tempered glass (TTG), ¼ inch thick, and with 8 mil anti-shatter film applied with a daylight application (i.e., film adhered to the glass surface without any mechanical attachment to the window frame). These windows were tested at a range of standoffs from the charge, in order to produce the full spectrum of injury from negligible to fatal. Additionally, tests were conducted with the following variability in the window configuration:

- Film: many tests were conducted without daylight film; one test used film that was mechanically attached to the frame.
- Glass type: annealed glass (AG) was used in place of TTG.
- Glass thickness: thicknesses of 1/8 and 3/8 inch were tested in addition to the nominal ¼ inch.
- Pane size: a 5 by 8 ft window was also tested, instead of the nominal 4 ft square.
- Protective measures: several tests used cable catcher systems, one positioned the ATD behind a computer monitor, while another used an off-the-shelf high-back chair instead of a standard office chair.
- Other: one test used a wood stud wall for debris generation in place of a window.

Note that the only injury mechanism being evaluated by these ATDs is blunt trauma to the head. Penetration injuries, or blunt trauma in other body parts, requires different kinds of instrumentation and was beyond the scope of these tests. Nevertheless, some qualitative information about the severity of potential penetration injuries from shards produced by unfilmed windows was gathered by wrapping the ATD's head in chamois and documenting the number, depth, and severity of the cuts sustained.

A summary of the relevant parameters for the 21 cubicles under consideration is presented in Table 1, as well as the positive phase peak pressure and total scaled impulse measured by gages directly on the front face of each cubicle, or on a culvert section immediately adjacent to the cubicle. In the comparisons to be made below, these measured pressures and scaled impulses will be used as the primary metrics of loading.

In addition to the accelerometers in the head of the ATD, the glass pane for filmed windows was instrumented with an accelerometer which provided data on the glass debris velocity. A high-speed film camera was also positioned within the room to record motion of the ATD and the glass. These film records were subsequently analyzed using digital imaging techniques to capture the position of the glass debris at various points in time, from which record the glass velocity could be deduced by differentiation.

Table 1. Summary of test parameters and measured loads.

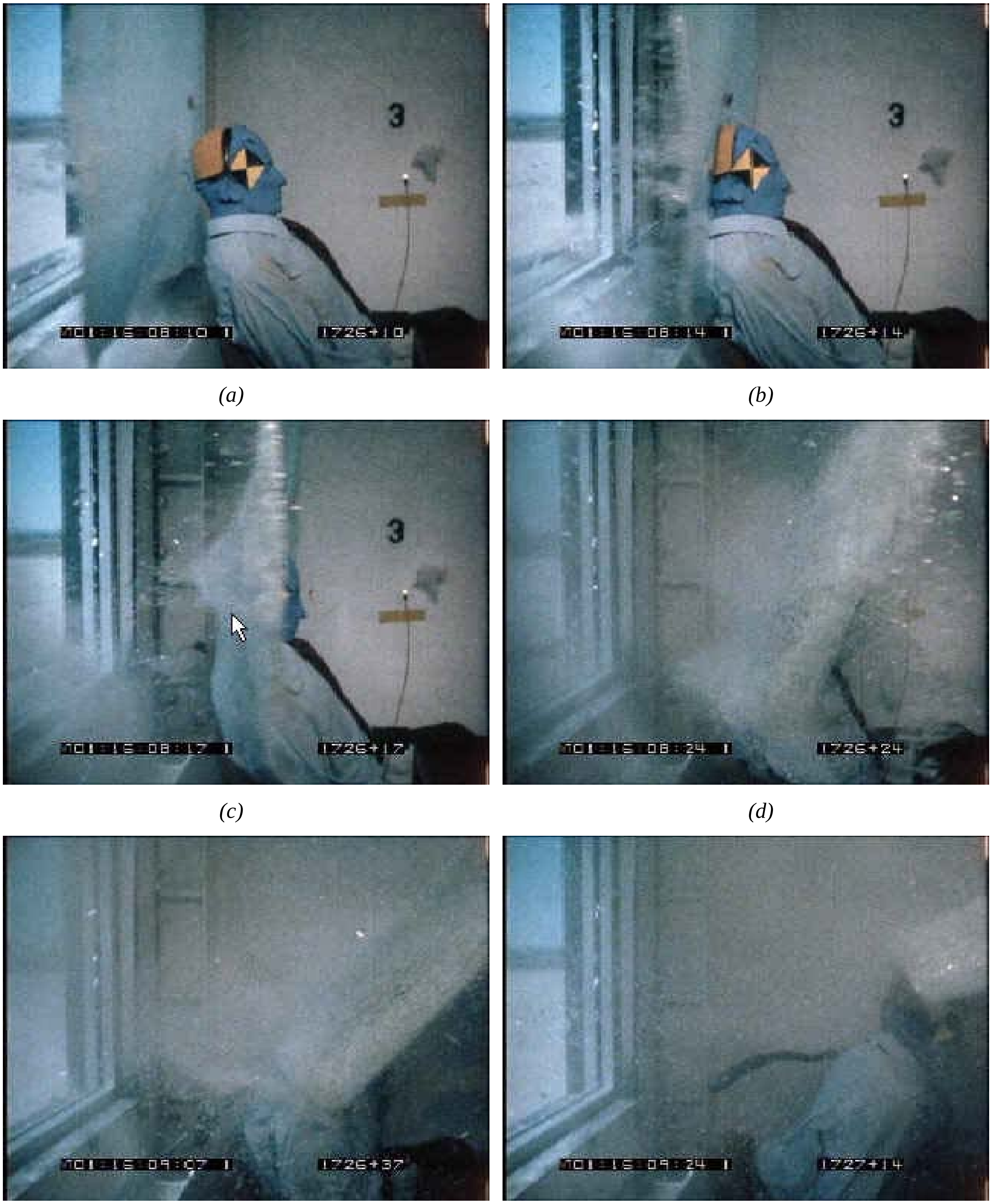
Test / Cubicle	Window size, Glass type	Retrofit	Peak Reflected Pressure (psi)	Scaled Positive Reflected Impulse (psi-ms/lb$^{1/3}$)
DB 21 / 1	4' sq., ¼" TTG	Daylight filmed	45	18.4
DB 21 / 3	4' sq., ¼" TTG	Daylight filmed	12	6.6
DB 21 / 4	4' sq., ¼" TTG	Daylight filmed	6	4.4
DB 24 / 1	4' sq., ¼" TTG	Daylight filmed; ATD in high-back chair	50	16.7
DB 24 / 2	4' sq., ¼" TTG	Daylight filmed; ATD behing computer monitor	63	19.7
DB 24 / 3	4' sq., ¼" TTG	(none)	50	18.5
DB 24 / 4	4' sq., ¼" TTG	(none)	11	4.5
DB 28 / 1	4' sq., ¼" TTG	(none)	26	12.0
DB 28 / 2	4' sq., ¼" TTG	Daylight filmed	30	12.3
DB 28 / 3	4' sq., ¼" TTG	(none)	12	6.9
DB 28 / 4	4' sq., ¼" TTG	Daylight filmed	12	6.7
DB 29 / 1	4' sq., ¼" TTG	Filmed with 2-sided Framegard support	26	11.2
DB 29 / 2	4' sq., 3/8" TTG	Daylight filmed	11	6.6
DB 29 / 3	4' sq., 1/8" TTG	Daylight filmed	6	4.4
DB 29 / 4	5' x 8', ¼" TTG	Daylight filmed	6	4.4
DB 30 / 1	5' x 8', ¼" TTG	Daylight filmed + cable catcher	49	17.3
DB 30 / 3	wood stud wall	(none)	32	12.2
DB 30 / 4	4' sq., ¼" AG	(none)	11	6.1
DB 31 / 1	5' x 8', ¼" laminate	Cable catcher	35	13.6
DB 31 / 3	none (open)	(none)	31	12.4
DB 31 / 4	4' sq., ¼" AG	Daylight film	11	6.1

TEST RESULTS

In all these experiments, the loads were significantly greater than the strength of the glazing, and so all the windows failed and were projected into the cubicle with varying magnitudes of velocity. The impact of the glass debris on the ATD produced shocks measured by the head accelerometers. Foam on the back wall of each cubicle allowed retrieval of some of the glass debris and provided information on the general debris trajectory.

For a typical example of the response of one of these ATDs (DB 21/3, with ¼ inch filmed TTG), Figure 3 shows a series of snapshots taken with the high-speed film camera, showing glass breakage, translation of the glass towards the ATD, impact against the ATD, and the subsequent motion of the ATD. The glass sheet then continues towards the back wall, where it was found after the test on the floor (Figure 4). Using the high-speed film records, the digitized glass position data was converted to velocity histories. In virtually every case, these showed excellent

agreement with the velocity obtained by integrating the acceleration record from the gage on the window, at least up to the time of head impact. An example is shown in Figure 5.



(a) (b) (c) (d) (e) (f)

Figure 3. Snapshots from film of ATD response in DB 21 / 3.

(a) Posttest position of ATD. *(b) Glass debris on floor near back of cubicle.*

Figure 4. Posttest views of DB 21 / 3.

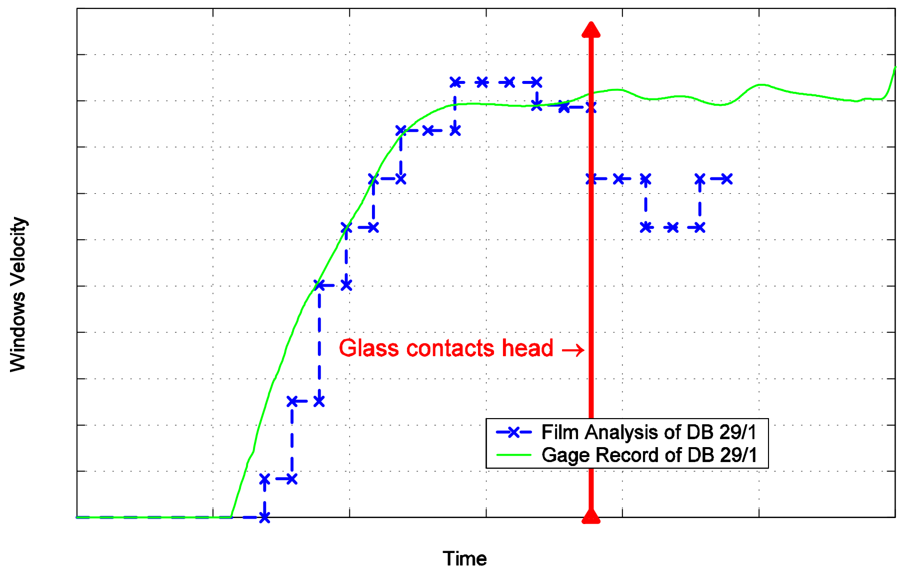


Figure 5. Typical glass velocity from analysis of high-speed film and integrated accelerometer record.

BLUNT TRAUMA INJURY ESTIMATION METHODOLOGY

We turn now to the injuries sustained by the ATDs. To be useful as a means of predicting levels of injury, responses measured in the test must be correlated to accepted criteria of injury. While such measures of response have not yet been developed specifically for blast scenarios, a number of metrics and criteria are widely used and available from the automotive safety industry.

To assess blunt trauma injuries for the ATDs in this test series, the triaxial acceleration histories measured by the three gages in the head of each ATD were combined to produce a single history of resultant acceleration (i.e., using the square root of the sum of the squares of the three components at each time step). This was then processed using an SAE class 1000 filtering

algorithm (as defined in FMVSS 208) with a cutoff of 1660 Hz. The filter eliminates components at higher frequencies than those to which the body can respond. The resulting history was then used to calculate the Head Injury Criterion (HIC), which is the most widely used criterion for head and brain injuries [2]. The HIC is calculated using the following equation:

$$HIC = \mathrm{MAX}\left\{\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}(t_2 - t_1)\right\} \tag{1}$$

In the above expression, $a(t)$ is the head center of gravity resultant acceleration expressed in g's and t_1 and t_2 are two arbitrary points in time. The method for HIC calculation is based on an algorithm described by Mentzer [3]. For test data in the form of a digitized time series, the HIC is obtained through numerical integration using the trapezoid rule spanning over a time range or a fixed time period. The algorithm also applies a partitioning technique to reduce the computation time.

The calculated HIC value for each ATD can then be compared to criteria to generate an injury level, generally characterized by the Abbreviated Injury Scale (AIS). The AIS is a numerical scale developed by the Association for the Advancement of Automotive Medicine and the American Medical Association [4, 5]. In the more than 20 years it has been in existence, it has become the most widely used injury rating system in the U.S. and internationally.

The correlation between AIS and injury levels is described in Table 2. In general, a HIC above 1,000 indicates a high probability of moderate brain injury and serves as the upper bound of permissible head injuries for federal automotive safety standards. Values above 1,500 correspond to a high probability of severe brain injury. Typically, AIS levels of 3 or greater are considered to be serious injuries, while an AIS of 6 indicates a fatality.

Table 2. AIS Severity Levels

AIS Level	Severity	Type of Injury
0	None	None
1	Minor	Superficial
2	Moderate	Reversible injuries; medical attention required
3	Serious	Reversible injuries; hospitalization required
4	Severe	Life threatening; not fully recoverable without care
5	Critical	Non-reversible injury; not fully recoverable even with medical care
6	Virtually Unsurvivable	Fatal

Equation 1 can be utilized with various durations (t_2-t_1). Because the debris impacting the ATD head in our experiments is relatively rigid compared to the head, a maximum duration of 15 ms was used to calculate all the HIC values for all the experiments. The use of 15 ms as a maximum duration is recommended for rigid debris, whereas a longer duration (e.g. 36 ms) is typically used in automotive safety studies to simulate impacts against more flexible objects such as padded objects inside a car (e.g., padded steering wheel, dashboard).

An example of the resultant acceleration history obtained in a typical automotive crash test for head impact against the relatively rigid A-pillar of a car (FMVSS 201U Automotive Occupant Protection Requirement) is shown in Figure 6. The duration of that pulse is roughly 5 msec. By comparison, the pulse width obtained in the blast tests varied from less than 2 to about 20 msec. Thus, for pulses in the 2–20 msec range, use of the car crash-based criteria like the HIC is reasonable and appropriate.

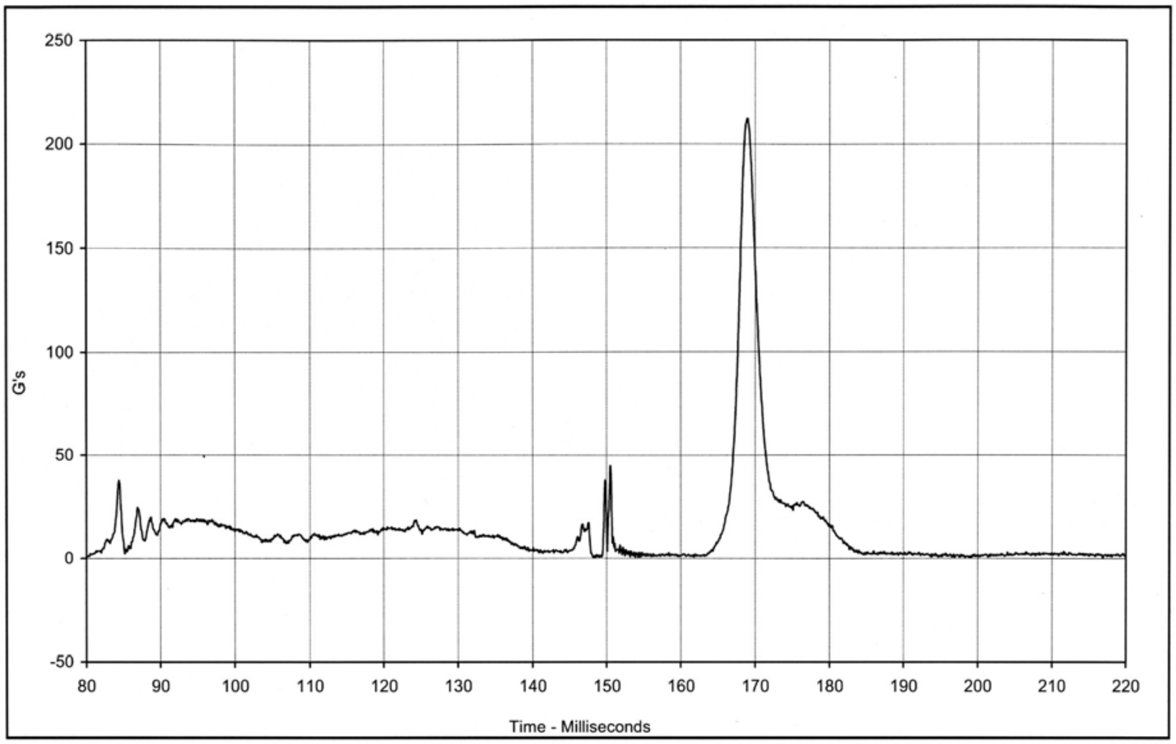


Figure 6. Typical head acceleration history from automotive crash test.

However, the literature does not support the use of HIC in the assessment of head injuries for impact durations less than 2 ms. (Typically, a 2 ms pulse width results in a HIC duration of approximately 1 ms or less.) Therefore, for pulse durations less than 2 ms, the injury assessment was based on an alternate lethality metric, the peak head acceleration, rather than the HIC.

After considering the various peak acceleration criteria for short-duration pulses in the existing literature [6, 7, 8], a set of acceleration criteria were established for use in this study. These augment criteria on HIC and are used whenever the HIC duration is less than 2 ms. This typically occurred for unfilmed glass at high loading levels, where the glass-head interaction occurs very rapidly. Filmed glass typically produced longer duration pulses. A summary of the criteria using both HIC and peak acceleration is presented in Table 3.

Table 3. Relationship between head response parameters and AIS.

AIS	Peak Acceleration (g's) [duration < 2 ms]	Head Injury Criterion (HIC) [duration > 2 ms]
0	< 60	< 50
1	60 - 220	50 – 250
2	220 - 300	250 – 750
3	300 - 360	750 – 1250
4	360 - 450	1250 – 1750
5	450 - 550	1750 – 2500
6	> 550	> 2500

EFFECT OF DAYLIGHT FILM ON BLUNT TRAUMA

We now consider the lethality results from the tests, in an effort to deduce general principles and trends, and to establish simple models for blunt trauma from glass. A subset of the most relevant and interesting comparisons will be discussed here; for the remaining comparisons, detailed documentation is available elsewhere [9].

Our attention is turned first to the effect of daylight anti-shatter film: does the provision of film enhance or reduce the lethality, and by how much? Since we have several data points at a range of load levels, with and without film, we are able to address this definitively.

Figure 7 plots the resultant head acceleration history from two tests, both with ¼ inch TTG, both at the same standoff, but one having film and one not. Clearly the presence of the film produces not only a much higher magnitude of acceleration, but also a broader, longer duration pulse. This duration is very significant because of its effect on the HIC calculation.

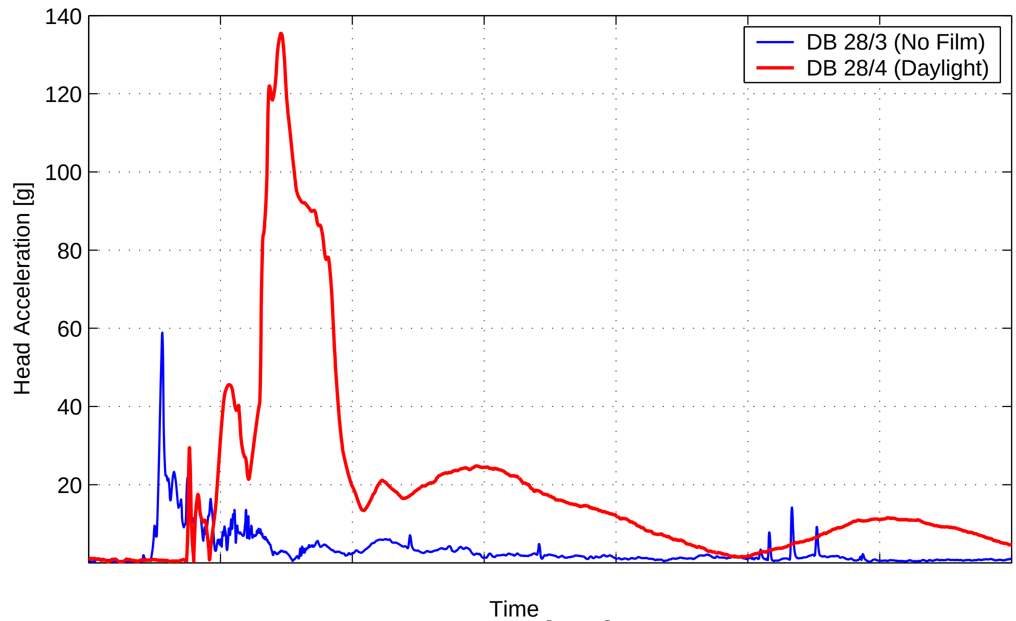


Figure 7. Effect of daylight film on resultant head acceleration histories.

It should thus come as no surprise that when we plot the AIS level as a function of the applied impulse for both filmed and unfilmed TTG windows, we find that filmed windows are more lethal, at least with regard to blunt trauma (Figure 8). And this is to be expected, since the filmed window is able to transfer more momentum into the head since the film creates a larger effective mass during the impact. On the other hand, the only portion of an unfilmed window that interacts with the head is that portion directly impacting the head.

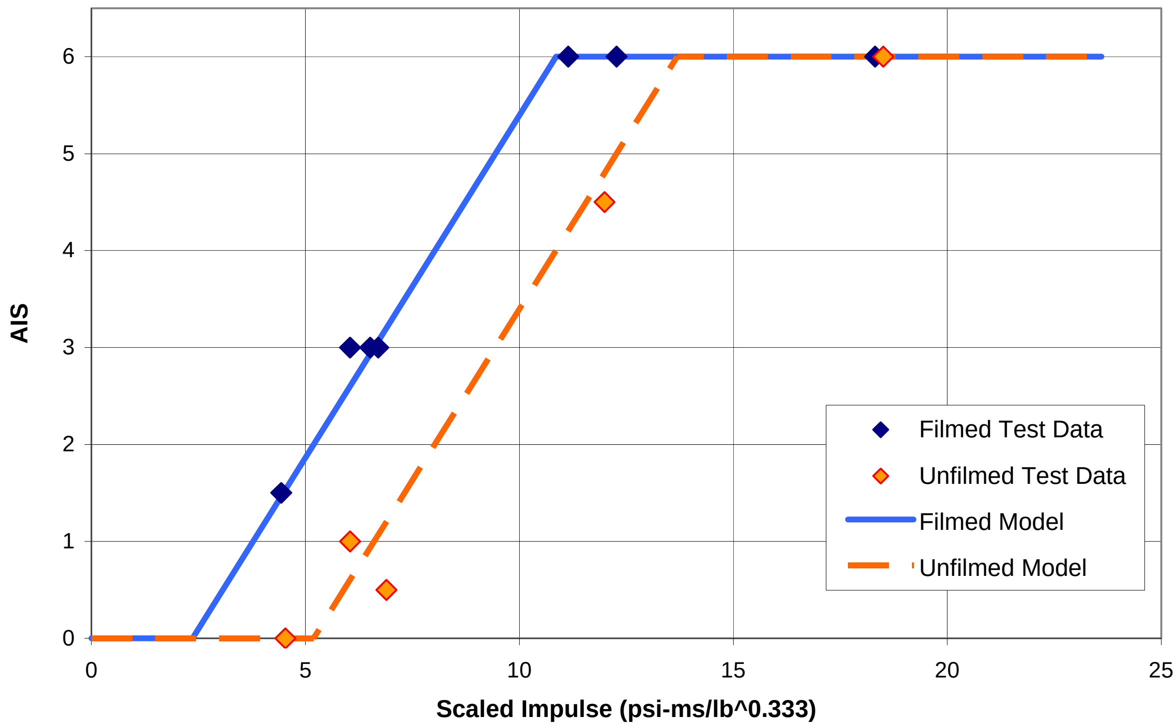


Figure 8. Blunt trauma lethality of filmed and unfilmed TTG.

The test data shown in Figure 8 are remarkably consistent and reproducible, as indicated by the multiple data points that lie near each other. Each point on the graph represents a single cubicle experiment, although the points span a number of tests at different standoffs.

Figure 8 indicates that, for a given level of impulse, filmed glass produces a more severe blunt trauma injury by about two AIS levels. Alternately, for a given level of lethality, an unfilmed window is able to experience a higher impulse level. Clearly, when the impulse is high enough, the presence or absence of film is inconsequential (see the two data points at scaled impulse of roughly 18 psi-ms/lb$^{1/3}$). It is noteworthy that the transition from negligible injury to fatality is accomplished over a very similar range of impulses for the two types of film (i.e., the two slopes are very similar), but the threshold of lethality is different (i.e., there is a shift between the two curves).

One may wonder whether the risk of penetration injuries nullifies the conclusions above, since daylight film essentially eliminates the propensity of glass shards to cause penetration injuries. Consideration of the chamois around the ATDs' heads suggests otherwise. Figure 9 compares the chamois from four different ATDs at different levels of loading. At the highest load level, the

cuts are severe, numerous, and potentially lethal. However, looking at Figure 8, that high level of impulse (18 psi-ms/lb$^{1/3}$) also produces a fatality through blunt trauma. At 12 psi-ms/lb$^{1/3}$, the cuts are less numerous and less severe, but the blunt trauma is still very high (between 4 and 5). While at the 6-7 psi-ms/lb$^{1/3}$ range, there are very few cuts and none of them appear severe. We can thus tentatively suggest that penetration injuries from unfilmed TTG will not control the overall lethality of the incident, but that blunt trauma will be the primary injury mechanism.

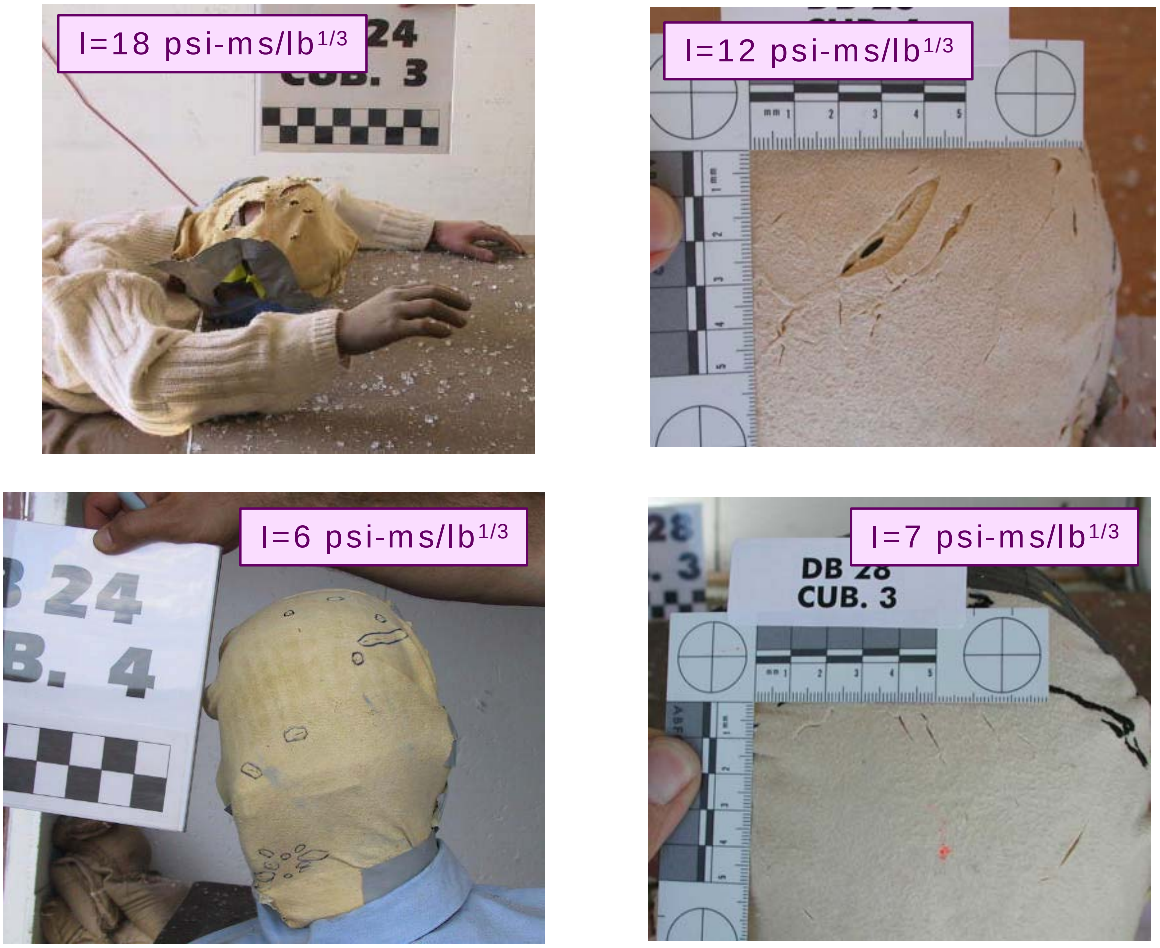


Figure 9. Cuts in chamois over ATD heads from unfilmed TTG shards.

EFFECT OF GLASS TYPE

Next, we consider whether AG or TTG produces greater blunt trauma lethality. Figures 10 and 11 plot the resultant acceleration histories for filmed and unfilmed ¼ inch glass, respectively, exposed to comparable loads. The comparisons indicate that for filmed glass, AG and TTG produce nearly identical response and identical lethality (as measured by HIC). For unfilmed glass, the AG response is greater, probably since the shards hitting the head are larger and greater net mass is coupled into the head motion. However, the magnitude of the increase is not sufficiently great to change the lethality by an appreciable margin. Hence, we can conclude that TTG and AG produce similar blunt trauma levels. With regard to penetration, however, AG should be more lethal, although these tests did not quantify that phenomenology.

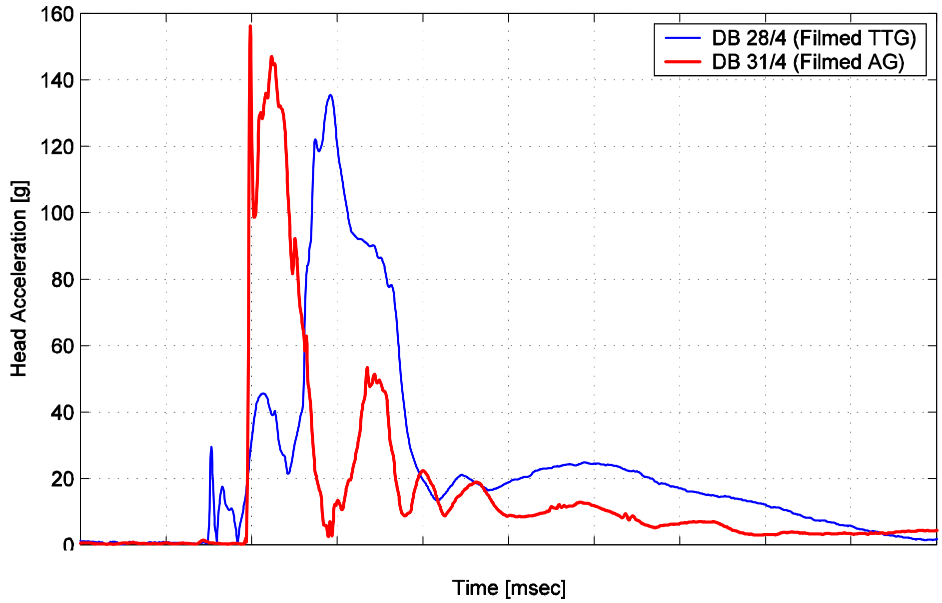


Figure 10. ATD head acceleration for filmed ¼" glass, comparing TTG to AG.

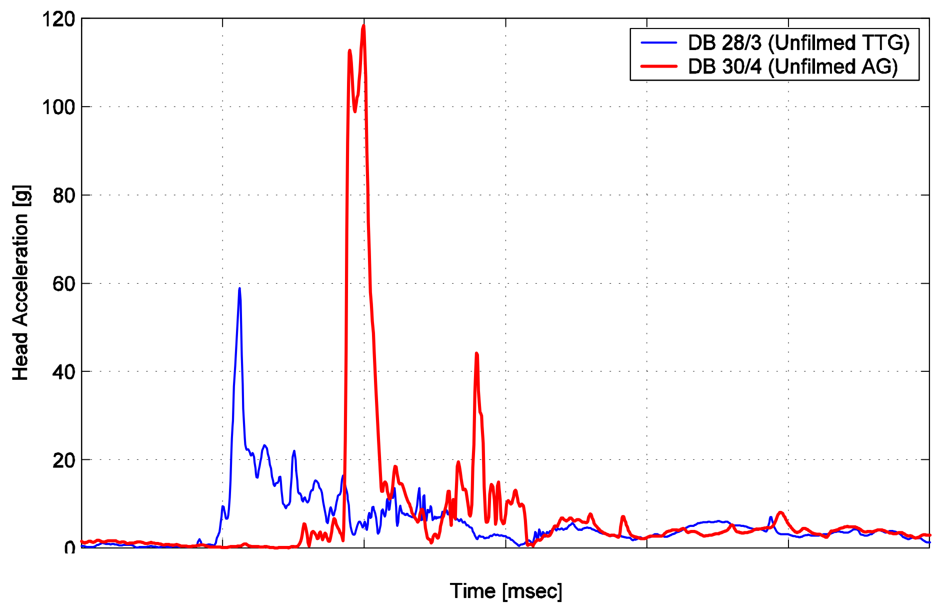


Figure 11. ATD head acceleration for unfilmed ¼" glass, comparing TTG to AG.

EFFECT OF GLASS THICKNESS

Comparing the response of the ATD impacted by ¼ inch filmed TTG to 1/8 inch filmed TTG, both at the same standoff and exposed to comparable loads, we note (Figure 12) that the two windows produce very similar acceleration histories, and nearly identical lethality levels. The 1/8 inch window travels twice as fast since it has half the mass (since velocity is directly related to the impulse divided by the mass), but the momentum in the thinner window is the same as that of the thicker window. Hence, the acceleration of the head is similar, and the lethality is similar.

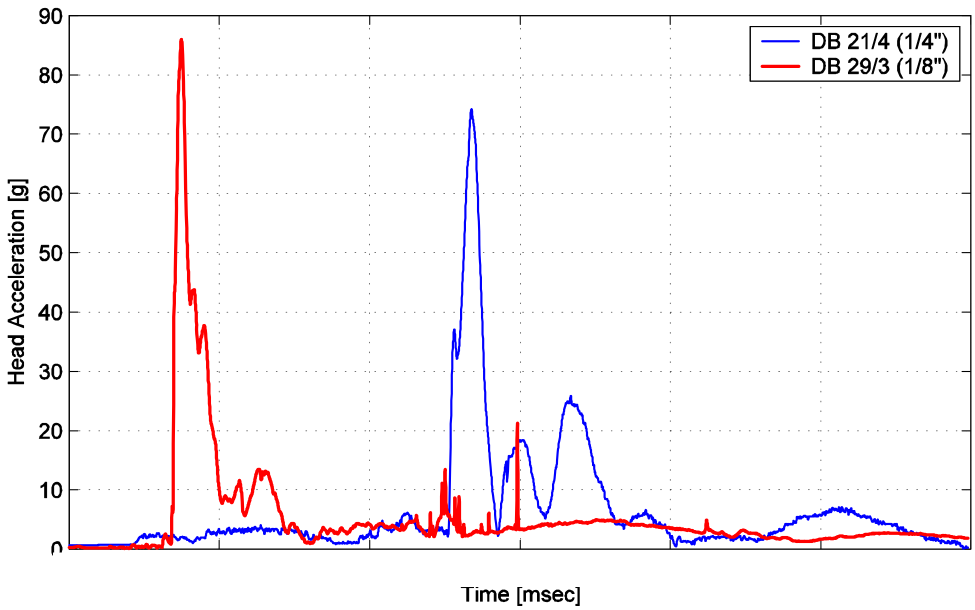


Figure 12. ATD head acceleration comparison for different thicknesses of filmed TTG.

PROTECTIVE MEASURES

A few types of protective measures were tested to assess their desirability as a means of reducing lethality. First, a simple off-the-shelf high-back chair was substituted for the standard low-back office chair used in the typical tests. The glass was still ¼ inch filmed TTG, and the standoff was very close with a high level of impulse. Another approach was to place the ATD behind a computer monitor, allowing the monitor to absorb the brunt of the ¼ inch filmed TTG glass debris and thereby protect the person.

The results, plotted in Figure 13, show that the high-back chair was ineffective at reducing lethality. The chair had a wooden frame that was unable to resist the impact loads of the glass and was broken in many pieces. Additionally, the density and stiffness of the foam padding used in the upholstery was such that it could not absorb much energy, simply transferring it to the ATD. The shielding provided by the monitor, however, was very effective. The vast majority of the glass missed the ATD, hence the very low signal level at the time of the glass passing by the ATD location. The glass did hit the monitor and caused it to translate at later time. Eventually, the monitor hits the ATD and generates the most significant lethality of the event. Much later, the monitor lands on the floor and (unluckily) on the instrumentation cables, producing the spurious spikes at very late time. A sequence of images from the high-speed film of this cubicle is shown in Figure 14.

In terms of the lethality of these scenarios, the high-back chair resulted in a fatality, as in the nominal case, but the presence of shielding by a monitor reduces the lethality from a certain fatality to a moderate chance of severe injury (from AIS 6 to 2), as seen in Figure 15. Additional measures, such as bolting the monitor to the table, could make this even more attractive as an means of improving survivability for typical office occupants.

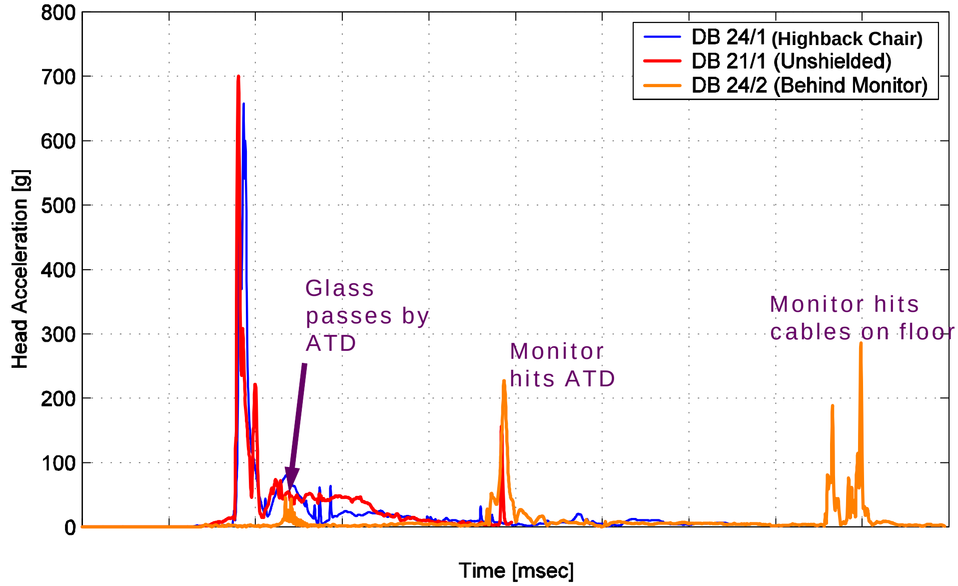


Figure 13. Head acceleration comparison for various protection measures.

(a) *(b)*

(c) *(d)*

Figure 14. Snapshots from high-speed film of ATD behind computer monitor.

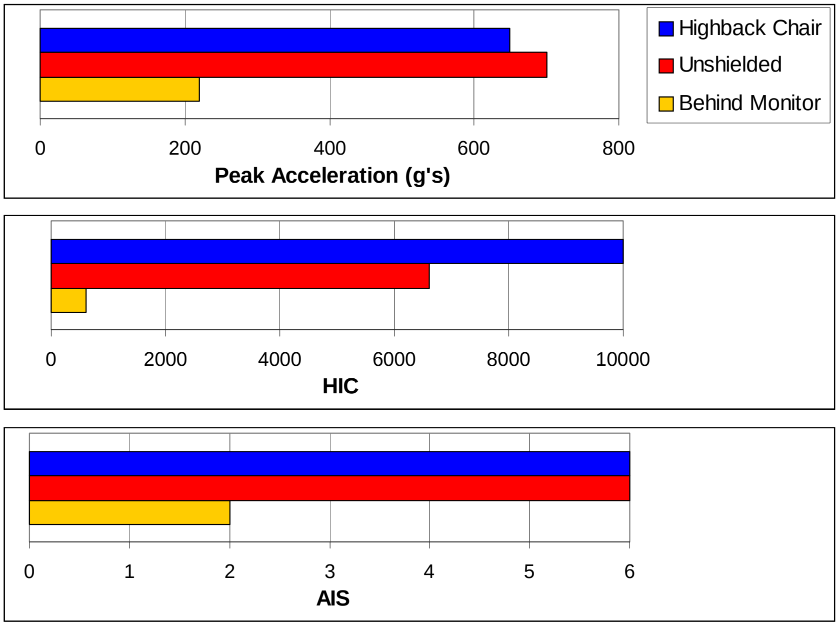


Figure 15. Lethality metrics for protective measures.

WOOD DEBRIS VS GLASS

One of the tests used a wood stud wall rather than a window to generate debris. Since this test was conducted at the same standoff as several of the window tests, we may compare the lethality to judge whether glass produces more severe blunt trauma than wood. It is noteworthy that the weight per unit area of the wood wall (2.8 psf) is comparable to the glass (3.3 psf), and the velocities are also quite similar (200 fps for glass compared to 170 for wood). Thus, if the lethality is directly related to momentum, we might expect comparable levels of injury. In fact, the wood ought to produce greater injuries since the effective mass of the impact would be greater, owing to the higher strength of the plywood and studs.

In fact, the reverse proved to be true. The acceleration histories, compared in Figure 16, show a much lower magnitude of response for the ATD behind the wood wall. The lethality metrics, shown in Figure 17, tell the same story: while the glass produced a certain fatality, the wood only produced a moderate injury (AIS = 2).

One likely reason for this is the way the ATD was situated relative to the wood wall (Figure 18). While the glass impacted a seated ATD who was reclining slightly backward, the wood debris impacted a standing ATD. The glass hit the head first, while a wood stud hit the chest first. In fact, the impact of the wood on the chest left a visible trace in the chalk on the ATD chest, confirming that the brunt of the impact was borne by the chest rather than the head. Most of the studs detached from the plywood, and the two are likely to have hit the ATD separately, rather than simultaneously, which would further reduce the consequences. Nevertheless, it is possible that the chest injuries (not measured in this test) would have exceeded the head injuries and produced a higher overall injury level.

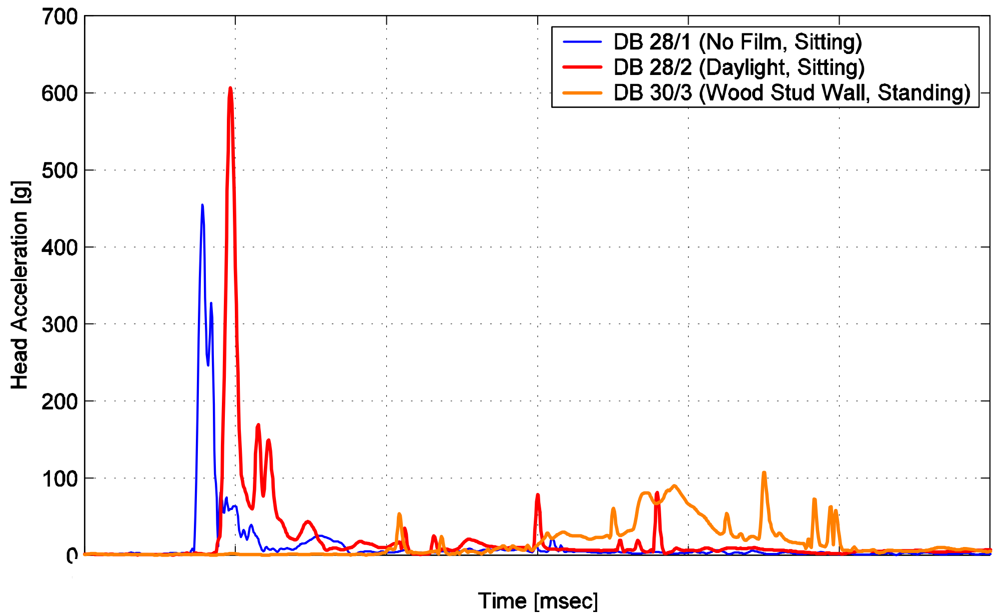


Figure 16. ATD head accelerations for filmed and unfilmed TTG vs wood debris, all at same standoff.

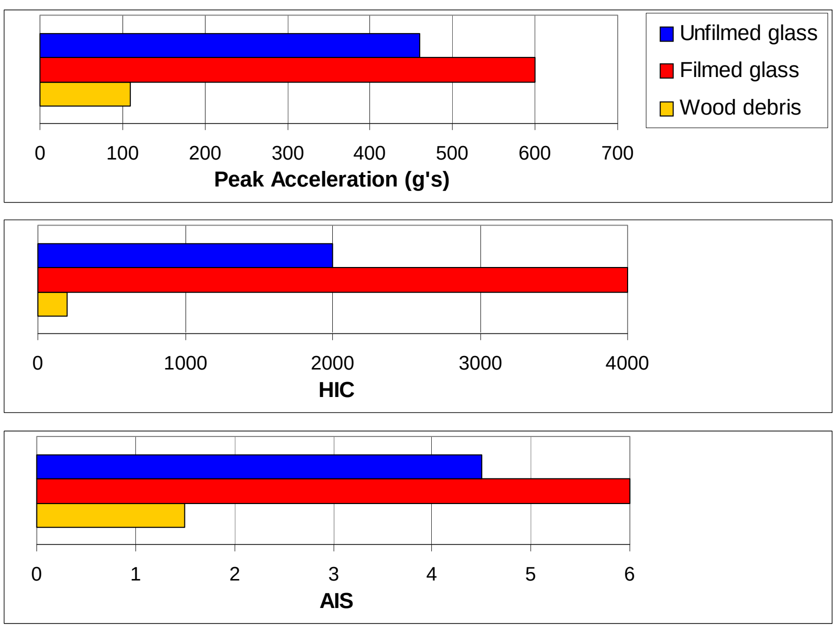
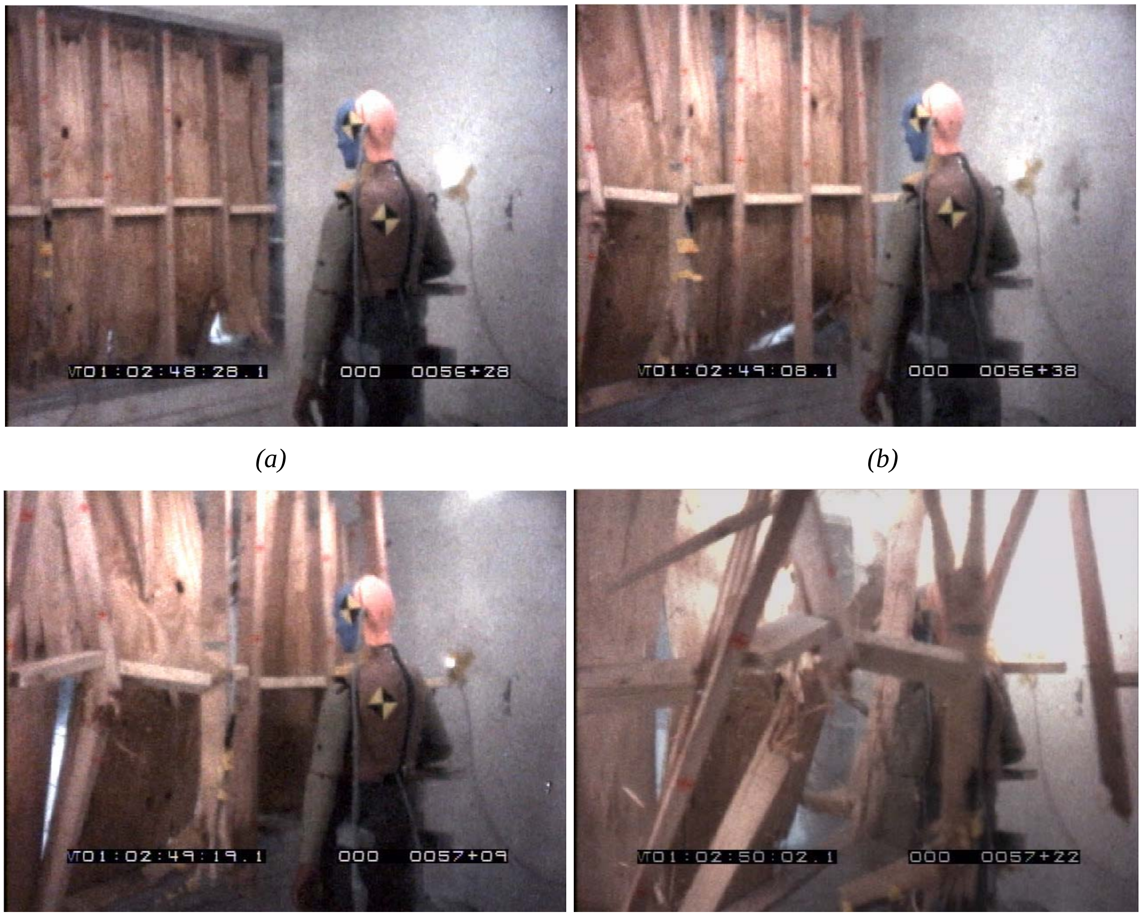


Figure 17. Lethality metrics for wood vs glass debris.

Nevertheless, the significant observation to be drawn from this is the sensitivity of human response to the minutiae of the interaction between the human and the debris. By having the ATD seated with his back to the window, maximum lethality was measured in the window tests. However, had the ATD been seated in a different position (e.g., leaning forward such that the glass would have hit the chair first), the resulting injury level could have been significantly different. Only further testing will reveal the magnitude of this difference.



(a) *(b)* *(c)* *(d)*

Figure 18. Snapshots of standing ATD impacted by wood debris.

CONCLUSIONS

The test data produced in this series of experiments reveals important trends which support significant conclusions regarding the blunt trauma lethality of glass. We observe that filmed TTG is as lethal as filmed AG; that filmed TTG is more lethal than unfilmed TTG, even when penetration is considered; that glass thickness is inconsequential to lethality, for loads of sufficiently high magnitude; that off-the-shelf high back chairs do not provide significant benefits, but shielding behind a monitor does; and that the response of the person is very sensitive to small changes in body position and attitude.

ACKNOWLEDGMENTS

The tests discussed in this paper were funded by the Combating Terrorism Technology Support Office, Technical Support Working Group (TSWG), with Mr. Robert Bezanson as program manager. These tests were executed by the Albuquerque Operations branch of the Defense Threat Reduction Agency (DTRA) in New Mexico. Technical direction of the program was

provided by DTRA, Ms. Audrey Kersul and Mr. Doug Sunshine. The authors wish to thank TSWG and DTRA for their sponsorship of this research and technical guidance.

DISCLAIMER

The opinions expressed in this paper are exclusively those of the authors. While the research discussed above was funded by the U.S. Government, this should not be construed to imply U.S. Government endorsement of any products or methods.

REFERENCES

1. D. Bogosian and H. Der Avanessian, "To Film Or Not To Film: Effects Of Anti-Shatter Film On Blunt Trauma Lethality From Tempered Glass," Proceedings of the 17th International Symposium on the Military Aspects of Blast and Shock, June 2002, Las Vegas, Nevada.

2. Backaitis, S. H., "The Head Injury Criterion," Head and Neck Injury Criteria, A Consensus Workshop, published by U.S. Department of Transportation, NHTSA, 1981.

3. S. G. Mentzer, "Efficient Computation of Head Injury Criterion (HIC) Values", Final Report DOT-HS-806-681, November 1984.

4. J. A. Pike, "Injury Scaling," Automotive Safety, Anatomy, Injury, Testing and Regulation, Published by Society of Automotive Engineers, Inc., 1990.

5. "Abbreviated Injury Scale, 1990 Revision," Association for the Advancement of Automotive Medicine, Des Moines, Iowa, 1990.

6. R. G. Snyder, D. R. Foust, and B. M. Bowman, "Study of Impact Tolerance Through Free-fall Investigation," Final Report for Insurance Institute for Highway Safety, December 1977.

7. P. Prasad and H. J. Mertz, "The Position of the United States Delegation to the ISO Working Group 6 on the Use of HIC in the Automotive Environment," SAE, PT-43, Biomechanics of Impact Injury and Injury Tolerance of the Head-Neck Complex, Published by Society of Automotive Engineers, Inc., 1993.

8. A. Kikuchi, K. Ono, and N. Nakamura, "Human Head Tolerance to Lateral Impact Deduced from Experimental Head Injuries Using Primates," SAE Paper 826035, 1982.

9. D. Bogosian, H. Der Avanessian, et al., "Assessment of Human Injury Data from Cubicle Experiments," Karagozian & Case and Biodynamics Engineering, Inc., TR-03-8, July 2003.